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The research performed by the Center for Accelerator Science and Technology (CAST) of the University of Texas at Arlington under Grant No. AFOSR-83-0368 during FY 83-87 can be classified into seven categories and the main achievements in each category are as follows. (1) Experiemtal investigation of electron beam physics: naturally occurring and externally driven low- frequency (6-500 KHz) diocotron oscillations are obersved and the m = 1 rotating structure of these oscillations are measured by using

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electrostatic probes, installed around an electron beam. (2) Systematic analysis of the circuit system for the generation of a fast-rising pinching magnetic field: a circuit consited of distributed circuit (transmission line) part and lumped circuit parts including a coil are systematically analyzed from the first principles of circuit. Computer code to calculate expediently the temporal profile of the pinching magnetic is developed. (3) Theoretical study of acceleration of high-energy electron beams by a laser-light through net inverse bremsstrahlung in plasma fields: it is found that the absorption of the incident laser photons by net inverse bremsstrahlung in an electric wiggler (plasma field) by the beam electrons having energies far greater than those in the free electron lasing can give rise to the dc ponderomotive force whose strength is far greater than the amplitude of the Lorentz force of the laser wave. (4) Study of a soft x-ray free electron laser (FEL) scheme using a two-beam elliptical pill-box wake-field cavity: it is found that the scheme provides sufficient gain as a coherent radiation source down to the x-ray regime. (5) Wake-field acceleration research: the theoretical result from the modal analysis developed here agrees with the recent experiment at Argonne National Laboratory in both profile (shape) and magnitude of the wake potential. (6) Development of a laser photocathode for the generation of high-current short-length electron bunch; the photocathode was constructed and improvements and refinements are still in progress under different auspieces, and (7) Design and construction of a modified betatron: a modified betatron called the UTA Modified Betatron was constructed.

INVESTIGATION OF ACCELERATION AND DENSIFICATION OF ELECTRONS UTILIZING TRAVELLING MAGNETIC WAVES

FINAL TECHNICAL REPORT OF RESEARCH PERFORMED UNDER GRANT NO. AFOSR-83-0368

Report Submitted to the Air Force Office of Scientific Research

by

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April 13, 1988

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Summary

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National Laboratory in both profile (shape) and magnitude of the wake potential. (6) Development of a laser photocathode for the generation of high-current short-length electron bunch: the photocathode was constructed and improvements and refinements are still in progress under different auspieces, and (7) Design and construction of a modified betatron: a modified betatron called the UTA Modified Betatron was constructed.

I. RESEARCH PERFORMED BY CATEGORY

Details in research performed in each category is as follows:

(1) Experimental Investigation of Electron Beam Physics

(a) Study of Diocotron Oscillations

Purpose: To develop a simple diagnotic means for the electron beam and to study behavior of an electron beam under influence of external fields.

Participants: Dr. K. W. Chen, Dr. S. H. Kim, Dr. D. K. De, M. C. McKinley
M. Kobold

Publications:

1. K. W. Chen, S. H. Kim, and M. C. McKinley, Low-frequency azimuthally propagating (diocotron) waves in a non-neutral electron beam column, Phys. Fluids 30, 3306 (1987).

2. November 4-8 1985 APS Plasma Physics Division meeting, San Diego, CA: K. W. Chen, S. H. Kim, and M. C. McKinley, Bull. Am. Phys. Soc. 31, 1392 (1986).

3. November 7-8, 1986, Stephen F. Austin University, Nacogdoches, Texas, Texas section of APS: M. C. McKinley, S. H. Kim, and K. W. Chen, Bull. Am. Phys. Soc. 32, 1185 (1987).

4. November 4-6, 1986, Baltimore, Maryland, APS Plasma Physics Division meeting: K. W. Chen, S. H. Kim, and M. C. McKinley, Bull. Am. Phys. Soc. 33.

Results

A steady-state electron beam is generated using an apparatus. which was operated in the 10^{-6} to 10^{-7} torr range. Two confining magnetic field coils

are arranged on the same vertical axis with coil currents supplied by a dc source. The current in each coil is directed such that the magnetic fields from the two coils add together forming a uniform magnetic field in the center of the apparatus. The magnetic field is directed upward. The injector consisted of a thermionic emitter (filament) located about 1 cm from a steel sheet, which, along with the filament, was parallel to the confining magnetic field. The stainless steel sheet was connected to ground via an ammeter. The potential of the thermionic emitter was varied from 0 to -3 KV using a DC power supply. The power supply was connected to the filament via an ammeter for measuring the injection current (current which leaves the filament). Emitted electrons move to the center region of the apparatus due to an E x B drift, then travel vertically upward or downward. The axial magnetic field provides both the magnetic field of the E x B drift and radial confinement of the plasma column. The plasma column is free to exit out of each mirror coil. A Faraday probe monitors the beam current which exits out of the lower confining coil. The upper portion of the beam passes through the upper confining coil and then through the radial wire probe assembly, and then impinges upon a ZnS:Ag screen. The ZnS:Ag screen is deposited on a thin film of tin oxide which is deposited on a pyrex disk. A positive potential can be applied to the tin oxide coating to accelerate approaching electrons to sufficient energy to excite the phosphor. Beam cross-sections examined using a ZnS:Ag plate were found to decrease with increasing confining magnetic field strength, and increase with injection voltage.

Natural oscillations were detected ranging from approximately 6.25 to 500 KHz and stably maintained without overt changes in external conditions: filament current, injector voltage, pressure and confining-field coil current.

The amplitude of the Faraday cup signal decreased as the beam cutter moved across the beam path, and decreased with the filament current. When an external electrostatic field was applied to the beam column, induced oscillations were also observed with radial wire probes.

We found by observing the signals from six needle electrostatic probe installed at six different positions around the electron beam that these naturally occuring and externally driven oscillations due to the m = 1 diocotron mode.

(b) Study of the Weibel Instability

Purpose: To study the mechanism to produce electromagnetic wave from an electron column

Participants: Dr. K. W. Chen, Dr. S. H. Kim, M. C. McKinley

Publications:

1. S. H. Kim, Electron cyclotron masing and the force due to net stimulated bremsstrahlung in an electron cyclotron maser using a dilute nonrelativistic electron beam, J. Plasma Phys. in press.

Results

Besides the low-frequency diocotron oscillations, we found also a high-frequency oscillation of 240 MHz. From the measured Faraday cup current, the electron density is far less than 10^7 cm^{-3} corresponding to the plasma frequency f_p = 30 MHz. Therefore, we can speculate that the observed high-frequency osscillation is not due to the electron plasma wave, which is electrostatic in nature. We measure this oscillation with a magnetic probe to determine whether this oscillation is due to an electromagnetic wave in near

future with the CAT's internal funds. We have reason to believe that these high-frequency oscillations to be due to the Weibel instability rather than the electron cyclotron maser instability since since our device happened by chance to be a very slow wave structure, i.e., $c >> v_p$ where v_p is the phase velocity.

(2) Analysis of the Circuit System for the Generation of a Fast-Rising Pinching Magnetic Field

Purpose: To pinch and accelerate electron beams

Participants: Dr. K. W. Chen, Dr. S. H. Kim, M. C. McKinley

Publications:

1. 5th IEEE Pulsed Power Conference, Crystal City, Arlington, VA, June 10-12, 1985: S. H. Kim, M. C. McKinley, and K. W. Chen, Hybrid circuit system analysis for the generation of a fast pinching magnetic field, Digest of Technical Papers, 5th IEEE Pulsed Power Conference, edited by P. J. Turchi and M. F. Rose, p. 693.

Results

The fast-rising high-voltage pulse generation circuit system of a theta pinch was theoretically analalyzed. The idealized model of this circuit system was a hybrid circuit system composed of three parts: a lumped circuit part consisting of a capacitor bank and a spark switch connected in series, another lumped circuit part consisting only of a single-turn pinch coil, and a distributed circuit part consisting of the Blumlein transmission line. The voltage difference between two ends of the pinch coil was formulated by analyzing this hybrid system by means of the law of the signal propagation in

the transmission line and Kirchhoff's law. An expedient numerical method for computer calculation was developed to generate the pulse profile of the voltage difference across the pinch coil.

(3) Theoretical Study of Laser Acceleration of High-Energy Electron Beams by Net Inverse Bremsstrahlung in Plasma Fields

Purpose: To find a means to accelerate very high energy electron beams to ultra high-energies in a very compact accelerator.

Participants: Dr. K. W. Chen, Dr. S. H. Kim

Publications:

1. S. H. Kim, Quantum-kinetic theory of free electron lasing in a spatially periodic longitudinal electrostatic field by a relativistic electron beam, J. Plasma Phys. 36, 195 (1986).

2. S. H. Kim, Electron cyclotron masing and the force due to net stimulated bremsstrahlung in an electron cyclotron maser using a dilute nonrelativistic electron beam, J. Plasma Phys. in press.

3. AIP's conf. on Laser Acceleration of Particles, UCLA, Los Angels, Ca, January 7-18, 1985 : S. H. Kim and K. W. Chen, Relativistic electron acceleration by net inverse bremsstrahlung in a laser-irradiated plasma, AIP Conf. Proc. No. 130 edited by C. Joshi and T. Katsouleas (AIP, New York 1985), p. 190.

4. January 4 -6, 1985 Texas section of APS, Rice University, Houston, Texas: S. H. Kim, Bull. Am. Phys. Soc. 30, 1097.

5. AIP's conf. on Optical Science and Engineering, Univ. of Texas at Dallas, Dallas, TX, November 18-22, 1985: S. H. Kim and K. W. Chen, Electron acceleration in a laser-irradiated plasma, Advances in laser Sciences - 1,

AIP Conf. Proc. No. 146, edited by W. C. Stwalley and M. Lapp (AIP, New York, 1986), p. 106.

6. SPIE's conf. on High Intensity Laser Processes, Quebec, Canada, June 2-4 , 1986 : S. H. Kim and K. W. Chen, Laser electron acceleration by net inverse bremsstrahlung, SPIE Vol. 664, edited by A. J. Alcock (SPIE, Belligham, WA, 1986), p. 87.

Results

The net dc force acting on relativistic electrons whose energies are far greater than those for free electron lasing by laser light in a longitudinal electrostatic plasma wave was calculated. It was found that the dc force due to the net inverse bremsstrahlung in the plasma wave can even exceed the oscillating Lorentz laser force when the electrons and laser wave co-traverse through a turbulent plasma. We rationalize this from the fact that the force due to net inverse bremsstrahlung (the absorption by inverse bremsstrahlung minus the emission by stimulated bremsstrahlung) is not included in the Lorentz force concept. The incident energy dependence of electron acceleration by co-propagating laser waves and the weaker longitudinal electrostatic waves was in qualitative agreement with the preliminary results of a recent Canadian laser-plasma electron acceleration experiment.

(4) Study of a Soft X-Ray Free Electron Laser (FEL) Scheme Using a Two-Beam Elliptical Pill-Box Wake-Field Cavity

Purpose: To develop a soft x-ray laser

Participants: Dr. K. W. Chen, Dr. S. H. Kim, Y. C. Chae, J. S. Yang

Publications:

1. S. H. Kim, Quantum-kinetic theory of free electron lasing in a spatially periodic longitudinal electrostatic field by a relativistic electron beam, J. Plasma Phys. 36, 195 (1986).

2. SPIE's conf. on Soft X-Ray Optics and Technology, Berlin, West Germany, December 8-11, 1986: S. H. Kim, K. W. Chen, and H. E. Wilhelm, Soft x-ray stimulated bremsstrahlung in traveling longitudinal electric wake-fields of two-beam pill-box cavities, SPIE Vol. 733, edited by E. E. Koch and G. Schmahl (SPIE, Bellignham, WA, 1986). p. 34.

3. SPIE's conf. on Innovative Science and Technology, Los Angeles, CA, January 10 -17, 1988: S. H. Kim and K. W. Chen, A soft x-ray free electron laser (FEL) using a two-beam elliptical pill-box wake-field cavity, SPIE Vol. 875 (SPIE, Bellingham, WA 1988).

Results

The lasing by stimulated bremsstrahlung of a relativistic dilute electron beam passing through a spatially periodic longitudinal electrostatic field (static electric wiggler) or a traveling undulating longitudinal electric field (traveling electric wiggler) was investigated. It was shown that this lasing is possible, and the gain increases with the inverse of the laser wavelength. Especially, a laser using a traveling electric wiggler provides sufficient gain to be used as a coherent radiation source down to the soft x-ray regime. In contrast, we found that the gain of the ordinary free electron laser using a transverse undulating magnetic field (magnetic wiggler) operating in the Compton regime decreases with the laser wavelength. We found that, among various possibilities, the wake-field produced in a two-beam elliptical or annular pill-box cavity is suitable as a traveling electric wiggler.

(5) Wake-Field Acceleration Research

Purpose: The overall goals of the program are to examine the theoretical basis of wake-field acceleration, possible application areas and to perform experimental proof-of-principle experiments. In deciding to study the elliptical cavities, we were motivated by the ease of fabrication of the cavity and that the gradient will be sufficient for future applications in compact accelerators and free-electron lasers. This work is continuing under support by a AFOSR grant 87-248.

Participants: Dr. K. W. Chen, Dr. S. H. Kim, Z. Chen, J. S. Yang, Y. C. Chae

Publications:

1. S. H. Kim and K. W. Chen, Modal analysis and its application to an elliptical pill-box cavity with finite apperture, Phys. Rev. A. to be published.

2. 6th International Conference on High-Power Particle Beams, Kobe, Japan, June 9-12, 1986: K. W. Chen and S. H. Kim, A compact high power/brightness wake field accelerator concept, Proc. of Beam'86.

3. SPIE's conf. on Innovative Science and Technology, Los Angeles, CA, January 10-17, 1988: K. W. Chen and S. H. Kim, Wake-field acceleration and compact accelerator considerations, SPIE Vol. 875 (SPIE, bellingham, WA 1988).

Results

A complete modal analysis was carried out which yields a full description of the wake-field acceleration mechanism. Experimental studies are in progress. The tenent of conclusions from previous studies is that the accelerating gradient should exceed 100 MeV/m per microcoulomb of charge and that the dominant wavelength of the wake-field is on the order of a few

centimeters, which is 20-40 times larger than the cavity gap, p. Conceptually, the fundamental wavelength L is related to the cavity gap p and the size of the cavity cross section r:

$$1/L^2 = 1/p^2 + 1/r^2 \ .$$

Thus the fundamental wavelength should be on the order of p, which is inconsistent with what was concluded previously that the dominant wavelengths of the wake-fields should be on the order of r. To investigate this apprarent inconsistency, a complete modal analysis was carried out. Our analysis include the fundamental assumptions which includes the validity of Maxwell equations, casuality, the Floquet theorem on a periodic structure, and that the energy gain is proportional to the number of the gaps. From this analysis, we found that the fundamental wavelength is on the order of r (not p) as in Publication 3. A recent experiment results obtained at Argonne National Laboratory remakably agree with this theoretical prediction on the fundamental wavelength. Further, the experimental profile of the wake-field is also in excellent agreement with the theretical profile obtained by us (Fig. 4 of Publication 3).

(6) Development of a Laser Photocathode for the Generation of High-Current Short-Length Electron Bunch (Work funded in part by the SDI)

Purpose: To use in wake-field acceleration and compact accelerator design studies

Participants: Dr. K. W. Chen, Dr. D. K. De, Y. C. Chae, J. H. Choe, S. Saifee, N. Ngon, P. Tien

Publications:

1. SPIE's conf. on Innovative Science and Technology, Los Angeles, CA,

January 10-17, 1988: K. W. Chen, Y. C. Chae, and J. Choe, Development of a laser photocathode for use in wake-field acceleration and compact accelerator design studies, SPIE Vol. 875 (SPIE, Bellingham, WA 1988).

2. November 4-7, 1987, Abelene, Texas, Texas section of APS: D. K. De, S. T. Saifee, K. W. Chen. Bull. Am. Phys. Soc. 33.

Results

A back-illuminating short-pulse photocathode using Cs_3Sb films for use in a 45-MeV electron linac was under development. The photocathode was designed for an optimum simplicity without requiring an in-situ cathode preparation procedure and to achieve a sufficiently high current density for use in an wake-field acceleration test currently underway. Preliminary tests performed at 6 kV/cm indicated that a current of 2.5 mA/cm^2 was satisfactorily achieved at a modest vacuum of 10^{-7} torr. However, fatigue effects were observed after a short period of operation in this test. Concurrently, a front-illumination metal photocathodes was also investigated for use in the wake-field test facility. Improvements and refinements are still in progress. The design of our photocathode is substantially different from those pursued elsewhere in that the harmonically generated Nd-YAG laser pulse (532 nm) is directed from the rear of the cathode surface, thereby simplifying substantially the laser optics. Use of the photoemitter of this type can be extended to other compact linac designs for commercial applications.

(7) Design and Construction of the UTA Modified Betatron

Purpose: To construct a high-current modified betatron with which we experiment to find whether the toroidal current is limited by the equivalent

principle like the Shafranov-Kruskal limit as in tokamaks.

Participants: Dr. K. W. Chen, Dr. S. H. Kim, M. McKinley, M. Kobold, S. Saifee, N. Ngon, P. Tien.

Publications: CAST internal report (87-5-21)

Results

A high-current modified betatron was designed to maintain best the radial force equibrium, that is, the continuously increasing centrifugal force can be best cancelled by the also continuously increasing centripetal force of $e(v \times B_v)$ where B_v is the vertical field produced by two vertical field coils. A modified betatron called the UTA Modified Betatron was constructd according to this design.

III. SUUMARY OF PUBLICATIONS

1. JOURNAL PUBLICATIONS

1. K. W. Chen, S. H. Kim, and M. C. McKinley, Low-frequency azimuthally propagating (diocotron) waves in a non-neutral electron beam column, Phys. Fluids 30, 3306 (1987).

2. S. H. Kim, Quantum-kinetic theory of free electron lasing in a spatially periodic longitudinal electrostatic field by a relativistic electron beam, J. Plasma Phys. 36, 195 (1986).

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2. CONFERENCE PUBLICATIONS

1. AIP's conf. on Laser Acceleration of Particles, UCLA, Los Angels, Ca, January 7-18, 1985 : S. H. Kim and K. W. Chen, Relativistic electron acceleration by net inverse bremsstrahlung in a laser-irradiated plasma, AIP Conf. Proc. No. 130 edited by C. Joshi and T. Katsouleas (AIP, New York 1985), p. 190.

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3. MEETING (ABSTRACT) PUBLICATIONS

1. January 4 -6, 1985 Texas section of APS, Rice University, Houston, Texas: S. H. Kim, Bull. Am. Phys. Soc. 30, 1097.

2. November 4-8 1985 APS Plasma Physics Division meeting, San Diego, CA: K. W. Chen, S. H. Kim, and M. C. McKinley, Bull. Am. Phys. Soc. 31, 1392 (1986).

3. November 18-22, 1985, Univ. of Texas at Dallas, Dallas, Texas, AIP meeting on Laser Sciences-1: S. H. Kim and K. W. Chen, Bull. Am. Phys. Soc. 31.

4. November 7-8, 1986, Stephen F. Austin University, Nacogdoches, Texas, Texas section of APS: M. C. McKinley, S. H. Kim, and K. W. Chen, Bull. Am. Phys. Soc. 32, 1185 (1987).

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